Innovative Confinement Concepts – Concept Exploration –

Scientific Achievements and Goals Opportunities and Issues

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ICC – CE Program supports many concepts

"Strong external field"			"Advanced toroidal and others"		
Tokamak innovations & physics	Spherical torus	Stellarator	Self-organized	Pulsed high-dens.	Other
High-Aspect ratio Tok. (ET) HBT-EP Resistive-wall stab. Tokamak trans. phys. Divertor innovation	Pegasus HIT-II LTX	HSX CTH QPS	Spheromak (SSPX, HIT-SI, CalTech) FRC (TCS-rotomak, Rotating field, SSX, Theory & Misc.)	Mag. Target Fusion (FRX-L, MTF sup., theory, stand-off driver) Accelerated FRC Inverse Z-pinch Flow Pinch (ZAP)	LDX CTIX Mary. Centr. Exp. Magneto-Bern. Exp. Inert. Elect. Conf.
$3.0M	$2.4M	$3.4M	$6.0M	$3.1M	$2.9M

ICC experiments and supporting theory/modeling are a focus of talent at many fusion laboratories

Universities	National Labs and Industries
Auburn	LANL
CalTech	LLNL
Columbia	ORNL
MIT	PPPL
Swarthmore	AFRL
UC Davis	GA
UCLA	
U. Maryland	
U. Nevada - Reno	
U. Texas	
U. Washington	
U. Wisconsin	

The ICC program is a vital contributor to the future workforce for the fusion energy sciences program

The NRC panels on *Burning Plasma Assessment* and on the *Assessment of the DOE OFES Program* both identified the need for a continuing influx of high-quality students to meet future workforce needs

- **ICC experiments at universities attract many students**
- **Both undergraduate and graduate students participate at the universities and through summer (or other) programs at the national labs**
- **Experiments at the national labs support many graduate students through collaborations with the universities**

ICC-CE funding supports:		**Lost at budget -10%**
Number of PostDocs	**14.5**	**– 2**
Number of PhDs awarded (since 1998)	**13**	
Number of graduate students within ~1 year of graduating	**12**	
Number of additional graduate students "in the pipeline"	**56**	**–17**

Undergraduate students are involved at a significant level

Many undergraduate students have contributed to the ICCs

- **Some continue in plasma and other physics areas**
- **Although most move into other careers, their experience in fusion physics is important for their understanding of and appreciation of science**

Some examples:

- **Swarthmore is an undergraduate school. Mike Brown's students have won many awards, and many are now graduating with PhDs from outstanding grad schools. This past year, one of his students, Matt Landreman became a Rhodes Scholar (Oxford)**
- **Ray Fonck built much of his experiment using undergraduate students. Ray also participates in a biannual Engineering EXPO with 2500-3000 visitors (grade-to-high school) every two years**
- **LANL has a major undergraduate programs (summer, DOE Fellows, NASA students, etc.), often with ~10 students participating in fusion projects**

Peer review is used to determine scientific quality

PoP programs are reviewed by panels, with each panel member submitting a personal, confidential report

- These reviews focus on science and on progress towards the energy goal
- The results have been highly positive
- The science focus is strengthened with advice for enhancing research on important issues

CE programs are reviewed on a 3-4 year cycle by 3 or more anonymous scientists

- This year, 12 renewal proposals were submitted
  - 8 received excellent or very good ratings and were funded
  - 2 received 1-year close out funds
  - 2 received 1-year funding and will need to re-compete for future funds
- 6 (of 26) new proposals were funded

The peer review process is working well and helping to ensure the quality of science in the ICC program

Many cross-cutting science issues are addressed by the ICCs

ICCs contribute to many science issues in plasma and fusion

- **These experiments also motivate interactions between fusion science and other scientific disciplines**

Examples illustrate the strength of science in the ICCs

- **Magnetic reconnection, magnetic turbulence and chaos in self-organized systems**
- **Effects of flow and flow-shear in suppressing instabilities**
- **Stability limits to plasma pressure**
- **Quasi-symmetry in three-dimensional systems**
- **Magnetic thermal insulation in wall-supported plasmas**
- **Acceleration of plasmas for injection into fusion devices for density profile control**

Magnetic reconnection is a fundamental process in astrophysical plasmas and in several ICC experiments

ICC experiments observe reconnection in a broad range of plasmas, broadening the basis for understanding the physics

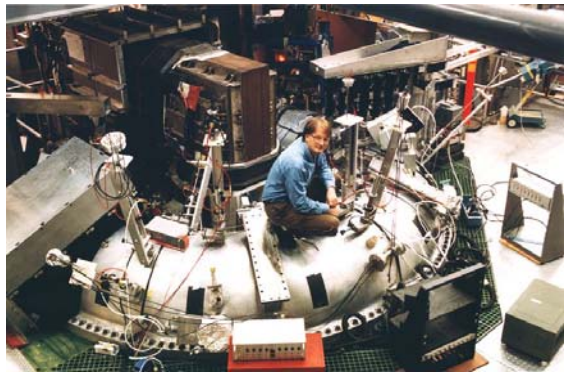
- **ST – a strong external toroidal magnetic field at low aspect ratio**
  - **Reconnection processes are similar to larger aspect-ratio tokamaks**
  - **At the lowest aspect ratios modes are similar to the spheromak**
  - **Coaxial helicity injection of current requires reconnection as spheromak.**
- **RFP – a moderate external magnetic field, a safety ratio less than one.**
  - **Study of tearing modes and the resulting transport of current from the ohmically driven core has elucidated dynamo physics**
  - **Understanding allows stabilization, increasing energy confinement.**
- **Spheromak – no external toroidal magnetic field, reconnection drives current.**
  - **Understanding allows tearing mode suppression, increased energy confinement.**
- **FRC – no toroidal magnetic field and no tearing in the conventional sense.**
  - **Plasmas formed in a regime intermediate to the FRC and spheromak quickly transform to one or the other by reconnection processes.**

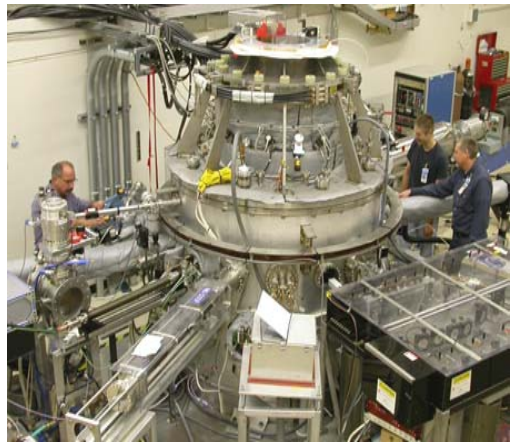
Development of new resistive MHD codes is strengthening our ability to understand the physic of reconnection in these experiments

Improved understanding of magnetic reconnection processes — used to improve energy confinement in MST and SSPX

MST

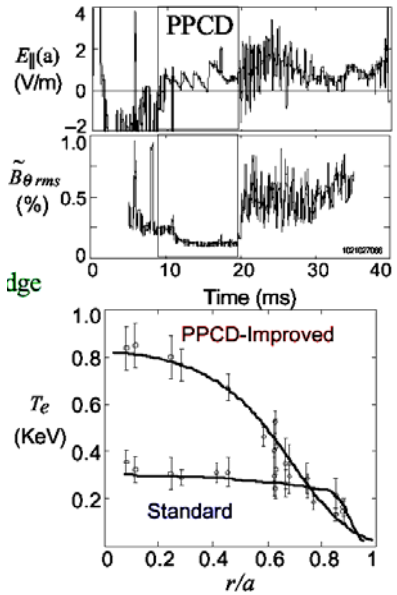
(U. WISC.)

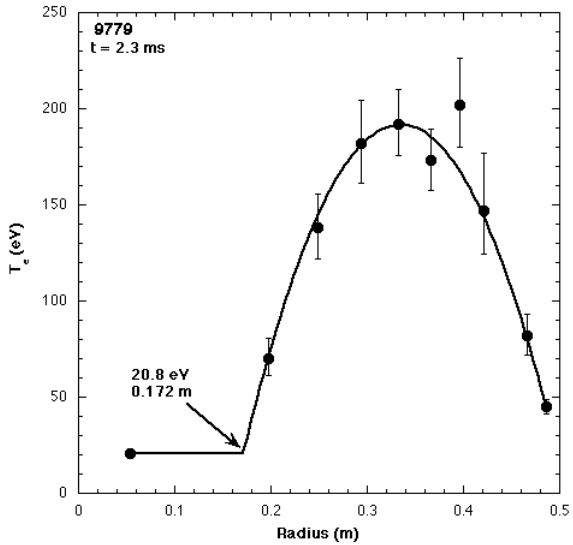




SSPX

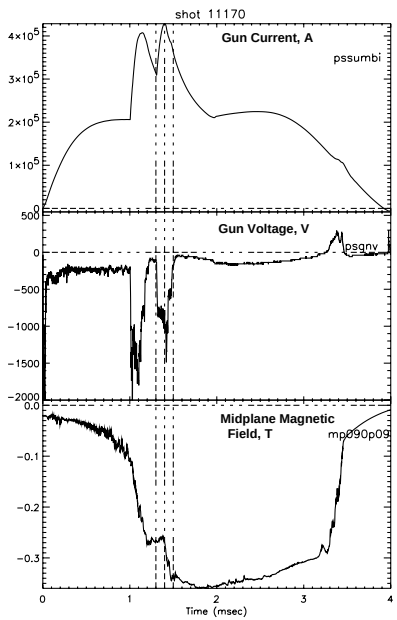
(LLNL)

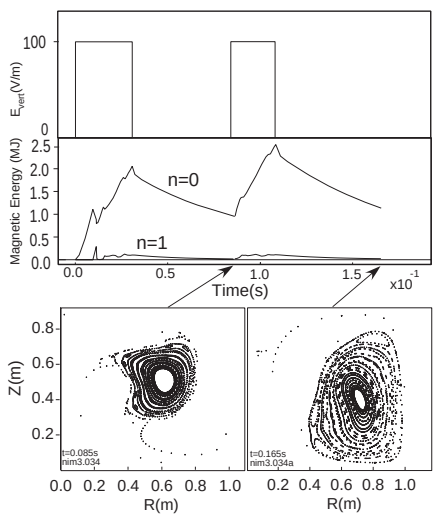




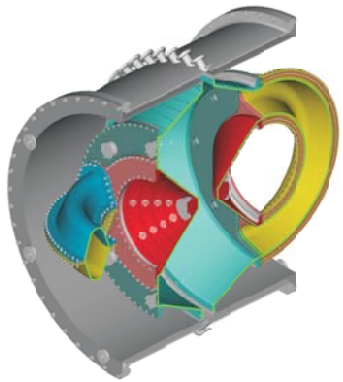
Helicity can be added steadily or in pulses to a spheromak

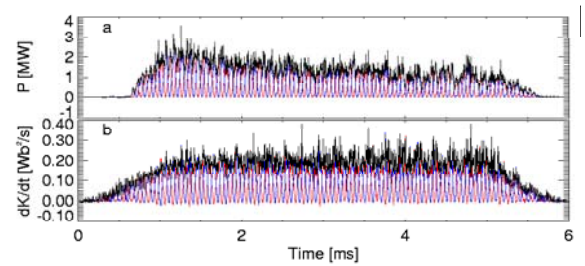
SSPX double-pulse experiment & NIMROD modeling





HIT-SI "push-pull" helicity injection



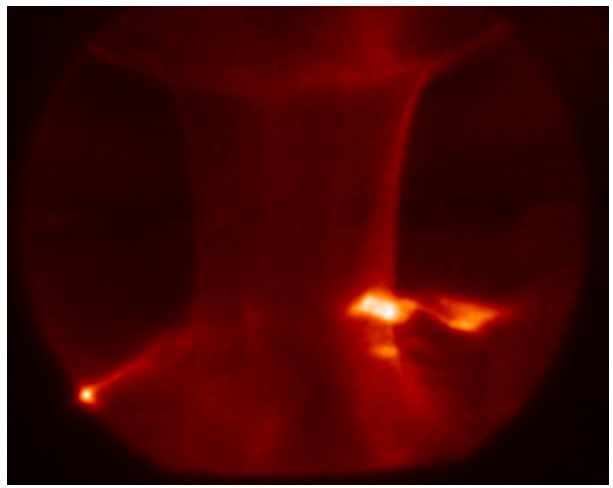


Spheromak initiation involves plasma merging and reconnection

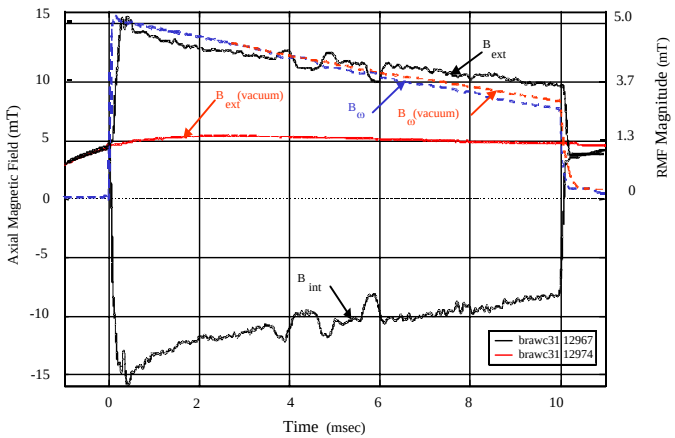
"Spider-leg" geometry in CalTech Spheromak Formation Experiment

This experiment connects solar-flare-relevant observations to reconnection processes laboratory experiments. Merging yields the plasma-curtain seen in initial stages in SSPX and from there by pinching and kink instabilities to the formation of the spheromak

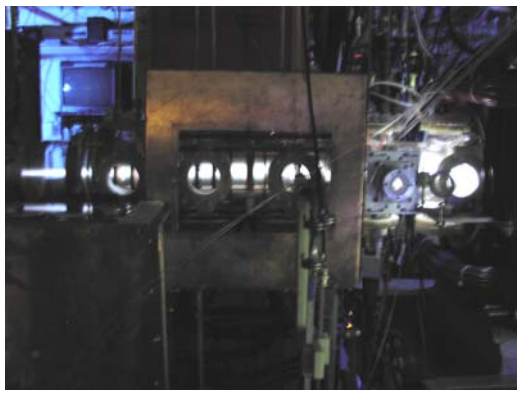
CalTech photo of the spheromak central column in SSPX (the spheromak is burned out)



Advances in FRC current drive by rotating magnetic field (RMF)



RMF extended to 10 ms using LANL power supplies. As plasma pulls away from the wall, the energy confinement time doubles (U. Wash.)



Odd parity RMF also extended to 10 ms with $n \approx 10^{18}$ m^{-3}, $T_e > 20$ eV (PPPL)

ICC theory: Two conceptual advances

- **Ryutov, Kesner, and Mauel have shown that closed-field-line systems are very sensitive to field errors**
  - **Small errors, ~ 10^{-6} can cause large excursions of field lines and give rise to significant neoclassical electron transport**
  - **Energy confinement in FRCs and levitated dipoles may be improved by small toroidal fields**

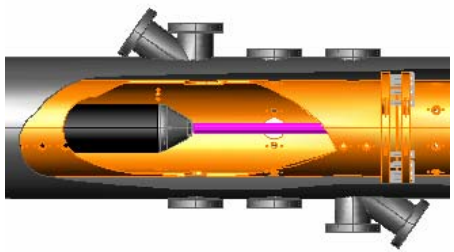
- **Parks and Thio have performed an exploratory analysis of the parameters required for fusion-burn from a MTF implosion using a spherical plasma liner (pulsed plasma jets)**
  - **Hypersonic jets (Mach > 50) will be required; gain is optimized at implosion velocities considerably less than used by ICF**
  - **If successful, this approach would allow a standoff between a MTF driver and the site of explosive energy release, allowing the reuse of hardware**

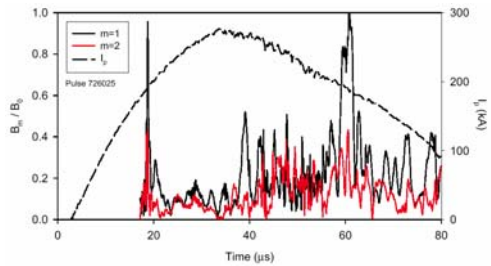
Effects of flow and flow-shear in suppressing instabilities

Role of flow shear in suppressing instabilities important to tokamak thermal barriers at edge and in core

It also is important in many ICC experiments:

- **NSTX – Tokamak physics applied at low aspect ratio**
- **ZAP – Shear flow stabilization in a linear z-pinch – experiment is motivated by MHD computational modeling**





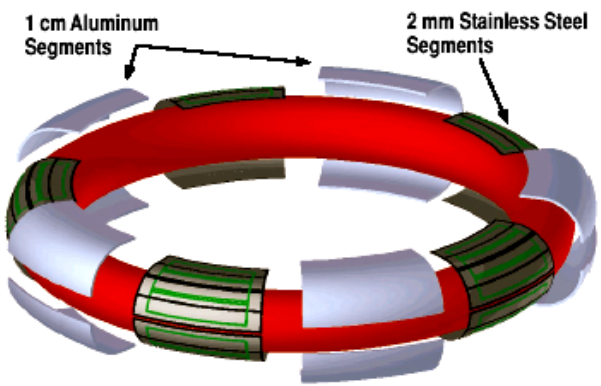
- **MCX – Strongly rotating plasma with rotational shear stabilization**
- **Magneto-Bernouli experiment – New equilibrium states with a strong sheared velocity**
- **HBT-EP – Plasma stabilization by conducting wall, rotation, and feedback**
- **RWM – Stabilization of resistive wall modes by rotating walls**

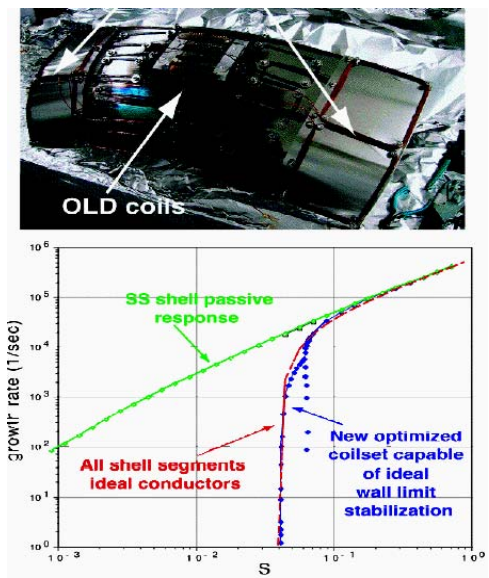
These experiments provide a broad basis for understanding the physics of plasma rotation and rotation shear in plasma stability

Stability limits to plasma pressure

Spherical torus (NSTX, Pegasus, HIT-II) – Obtaining high beta by stabilization of MHD modes at low aspect ratio

Tokamak (HBT-EP) – Stabilization of MHD modes by conducting walls, rotation and feedback to obtain high beta





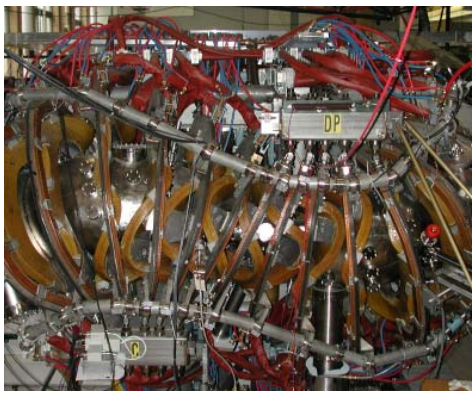
ET – Finding a path to high beta in a large tokamak

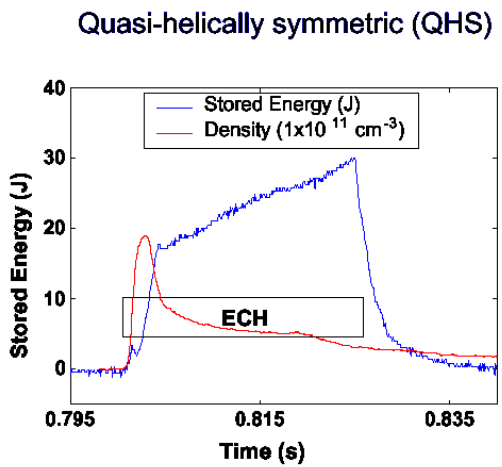
Levitated dipole (LDX) – Innate stability in an axisymmetric dipole field – exploring fundamental pressure limits in magnetized plasmas

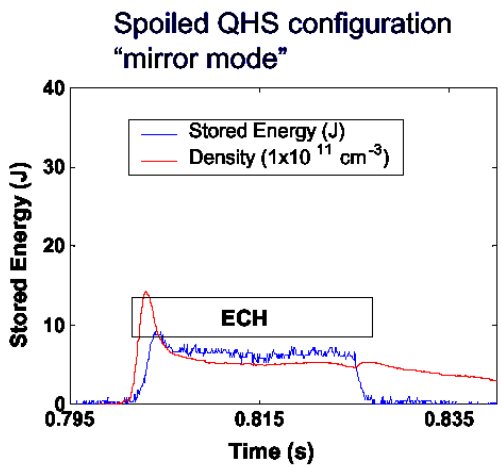
Quasi-symmetry in 3 dimensional systems

Stellarator experiments are exploring the effects of "quasi-symmetry" in three dimensional geometries. (In quasi-symmetry, particle motion can be described in terms of two generalized spatial dimensions.)

- **NCSX (under construction) – Quasi-axisymmetry**
- **HSX – Quasi-helical symmetry**

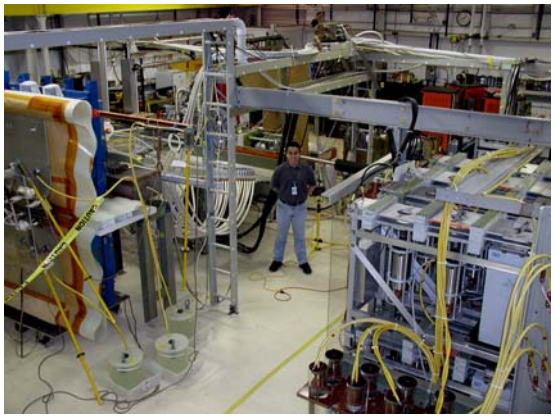




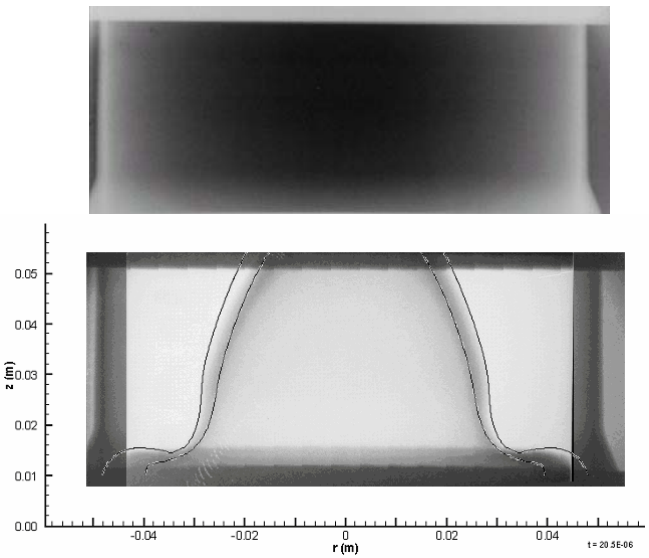


- **QPS (conceptual design) – Quasi-poloidal symmetry (related to linked mirror concepts)**
- **CTH – Stability and disruptions due to current in the stellarator configuration**

MTF has a predictive capability for large-bore liner implosions



FRX-L FRC experiment at LANL now routinely generates plasmas at 1-4×10^{20} m^{-3} and T_e = 200-400 eV, close to the requirements for a compression experiment.



Liner compression modeling and experiments are in excellent agreement for large diameter liners. The top photo is of the bottom 4.5 cm of a liner (9.8 cm diameter, 30 cm long) before implosion, and the bottom is an overlay of the implosion experiment and model.

The ICC workshop this year is focusing on major science and other broad issues

ICC2004 – U. Wisconsin May 25-28, http://plasma.physics.wisc.edu/icc2004/index.htm

Magnetic Relaxation and Confinement

***Generalized Cowling Theorem*, Allen Boozer**
***Relaxation in MFE Experiments*, Tom Jarboe**

Effects of Plasma Flow and Flow Shear

***Effects of Flow and Flow Shear in NSTX*, Jonathan Menard**
***Suppression of Turbulence and Transport by Sheared Flow*, Paul Terry**

FRC/ MTF: Physics, History, and Status

***FRC History, Physics, and Recent Developments*, Alan Hoffman**
***New Results in Plasma Implosion Techniques*, Tom Intrator**

Stellarators

***Stellarator Physics and Status of World Program,* Mike Zarnstorff**
***Electric Fields in Stellarators*, Thomas Pederson**

Inertial Fusion Energy

***Tutorial on IFE*, Mike Cambell.**
***Innovations in Heavy Ion Fusion*, Simon Yu**
***Innovations in Z-Pinch Fusion*, Craig Olson**

Networking

***Grid Computing and Collaboration Technology in Support of ICC*, Dave Schissel**

Plasma Diagnostics and Modeling

***Reconstructing Experimental Equilibria*, Steve Sabbagh**
***MHD "Spectroscopy,"* Dave Maurer**

Gas Dynamic Trap

***Advances in GDT Physics*, Alexander Ivanov**

Reactors

***The Physics of Fusion Energy*, John Perkins**
***Reconsidering Old Ideas*, Simon Woodruff**
***D-3He Physics and Fusion Energy Prospects*, John Santarius**

Friday morning will focus on input to the FESAC Priorities Panel

Opportunities to strengthen the ICCs (1)

(A) Budget issues

1996 Report of the *FESAC-SciCom Review Panel on Alternate Concepts*

- **Defined the program and levels of experimentation — Concept Exploration, Proof-of-Principle, Proof of Performance & Optimization, Fusion Energy Development, Fusion Power Demonstration Plant**
- **CEs — experiments costing less than $5M/year and/or theory that**
  - **Strive at establishing the basic feasibility of a concept**
  - **Explore phenomena of interest and benefit to other concepts**

Today, the largest CE experiment is funded at $2.5M

Given inflation, these levels are low and make it difficult to achieve scientific progress to the depth needed to move to the next step.

Recommendation: Close the "funding gap" – Improve the funding of lead CEs

Issue: Where do the funds come from?

Opportunities to strengthen the ICCs (2)

(B) Cross-cutting diagnostics for the CEs – to strengthen the science

- **The CEs are limited in diagnostic capability**

Recommendation: Establish a diagnostic program focused on the ICCs

- **Goal: Improve the scientific output of the CEs — Perhaps key diagnostics could be portable and moved among several experiments to generate cross-cutting results – Diagnostics issues are on the ICC2004 agenda**

(C) Theory and Modeling initiative for the ICCs

- **Theory and modeling needs strengthening for the ICCs**
  - **T&M is key to understanding and interpreting experimental results**
  - **T&M can also provide guidance in conducting experiments**

Recommendation: Provide funding opportunities explicitly supporting the CEs, both to interpret specific experiments and to apply the understanding across the portfolio

Both efforts would strengthen scientific coupling to the PoPs, tokamaks, and burning plasmas

Summary — The Innovative Confinement Concepts are significant contributors to plasma and fusion science

The ICCs are addressing fundamental science which is also important to the tokamaks and to burning plasmas

The science is strong and guided by peer-review

As we move forward, we need to encourage the best science we can

— However, the tight funding will keep progress slow

The experiments and supporting theory/modeling contribute to allied areas of science and technology, as called for by the NRC

The ICCs attract students to the Fusion Science Program, helping address the need for future scientists and engineers

The ICC program should be strengthened in the Burning Plasma era

It provides breadth, scientific insight and knowledge, and opportunities for innovation — helping to build a strong base for future Fusion-Energy Sciences